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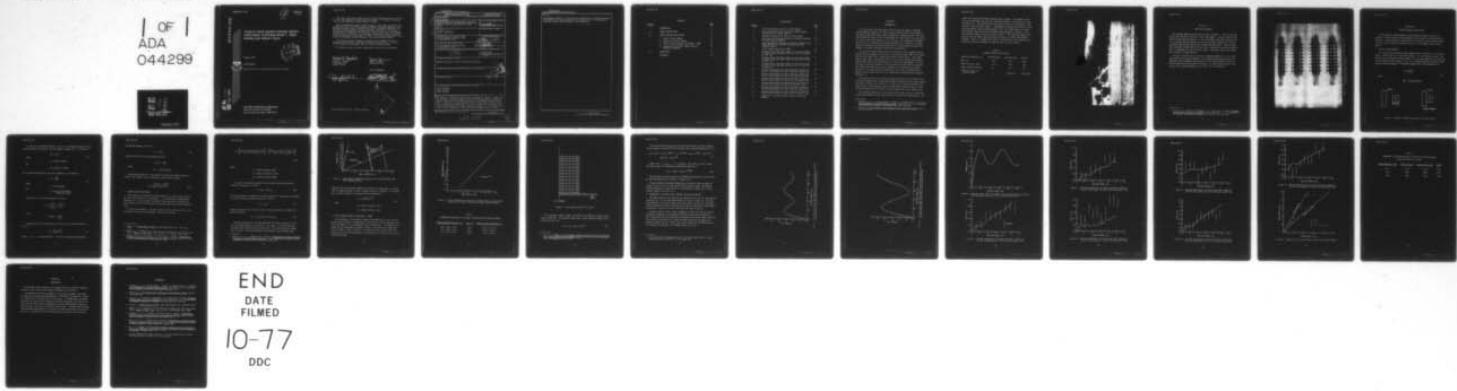
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**TITAN III SOLID ROCKET MOTOR IMPACT
STRUCTURAL RESPONSE, PHASE I: BARE
PROPELLANT IMPACT TESTS**

August 1977



Final Report

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**AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117**

This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, under Job Order 20070324. Lt Michael L. Crawford (NSQ) was the Laboratory Project Officer-in-Charge.

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This technical report has been reviewed and is approved for publication.

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Force Weapons Laboratory. The purpose of the program is to define the breakup and dispersion of solid propellant in the unlikely event of a launch abort involving a launch vehicle fueled with this material.

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SECTION I

INTRODUCTION

On 2 July 1976, a 66.8 kg (30.5 by 30.5 by 40.6 cm) sample of UTP-3001 solid propellant (used in the Titan III space launch vehicle) was impacted at the Area V rocket sled track, Sandia Laboratories, Albuquerque, NM. This test was followed on 8 July by a 24.1 m/sec impact of a 50.2 kg, 30.5 cm cube and on 22 July by a 24.4 m/sec impact of a 61.0 cm cube. The purposes of the impact tests were (1) to demonstrate the ignition sensitivity of UTP-3001 to impact and (2) to prove or to disprove the ability of a finite element computer code (HONDO) to calculate the impact stresses and deformations.

This series of impact tests is the first phase of a test program aimed at determining the response of the Titan III solid rocket motor (SRM) to an impact such as would result from a launch pad accident (launch abort). The second phase of the impact test program will be a series of scaled SRM model impacts, and the final phase will be the impact of a full-scale SRM segment. The ultimate goal of the test program is to qualitatively and quantitatively describe the breakup and dispersion of solid propellant in a launch abort situation. The data will be used for future assessments of the risk of launching large amounts of radioactive material, e.g., radioisotopic thermoelectric generators (RTG) (ref. 1).

The three UTP-3001 solid propellant samples were cut from a salvaged Titan III-C motor segment using a technique developed in-house by the Air Force Weapons Laboratory, Kirtland AFB, NM (ref. 2). A set of grid lines was painted on one face of each of the propellant cubes for observable deformation data, and the test-ready samples were delivered to Sandia Laboratories for the impact tests.

The impacting surface was a 6-inch-thick armor plate, which was accelerated through approximately 75 feet using from five to seven Zuni rocket motors. The

1. Kelleher, D., E. W. Holtzscheiter, J. Sholtis, G. Mitchell and M. L. Crawford, Safety Methodology for Space Nuclear Systems, AFWL-TR-77-104, Air Force Weapons Laboratory, Kirtland Air Force Base, NM, to be published.
2. Robinson, R., Solid Rocket Motor Preparation and Propellant Cutting, AFWL TR to be published.

rocket sled weighed approximately 8,000 pounds at impact. The impacting steel plate was accelerated into the solid propellant samples, and there was no "back-up" medium (i.e., the propellant was not constrained and was accelerated to the velocity of the sled after impact). Photographic coverage was provided by Fastax and Hycam cameras, which operated between 16,714 and 21,008 frames per second. These cameras recorded the grid deformation data presented in section 3.3 and the time after impact of ignition shown in table 1. Two additional cameras were used for the sled impact velocity determination and for overall photographic coverage. Figure 1, a frame taken from the "sled velocity" film, shows the propellant and sled at the moment of impact for the 24.1 m/sec impact.

Table 1
OBSERVED IMPACT IGNITION DATA

Propellant Dimensions, cm	30.5x30.5x30.5	30.5x30.5x 40.6	61x61x61
Mass, kg	50.2	66.8	401.8
Impact Velocity, m/sec	24.1	24.4	36.0
Impact Ignition Observed	No	Yes	Yes
Time After Impact of Ignition, msec	--	0.86(± 0.05)	0.57(± 0.05)



Figure 1. 24.1 m/sec Impact of the 30.5 cm Cube Sample

SECTION II
IMPACT IGNITION DATA

The observed impact ignition data are shown in table 1. The 67 kg and the 402 kg cubes ignited in less than 1 msec after impact. The 50 kg cube did not exhibit impact ignition; however, it did ignite after rebounding from the sled. It is believed that the ignition was caused by friction between the tumbling propellant cube and the sand which surrounded the sled track. Figure 2 shows four consecutive frames from the Fastax camera, from which the grid deformation data were obtained, for the 24.4 m/sec impact. The third frame clearly shows the initiation of impact ignition.

The data in table 1 are included for reference purposes only. Due to the unavailability of critical parameters (the propellant activation energy, the exothermic bulk degradation pre-exponential factor, the propellant pyrolysis melting exponent, and the Gruneisen constant), an impact ignition model correlation, such as that developed by Krier (ref. 3), is not possible.

3. Krier, H., H. H. Hiton, O. Olorunsola, D. L. Reuss and J. M. Foley, An Impact Ignition Model for Solid Propellants, Contract Report No. 157, US Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD, June 1974.

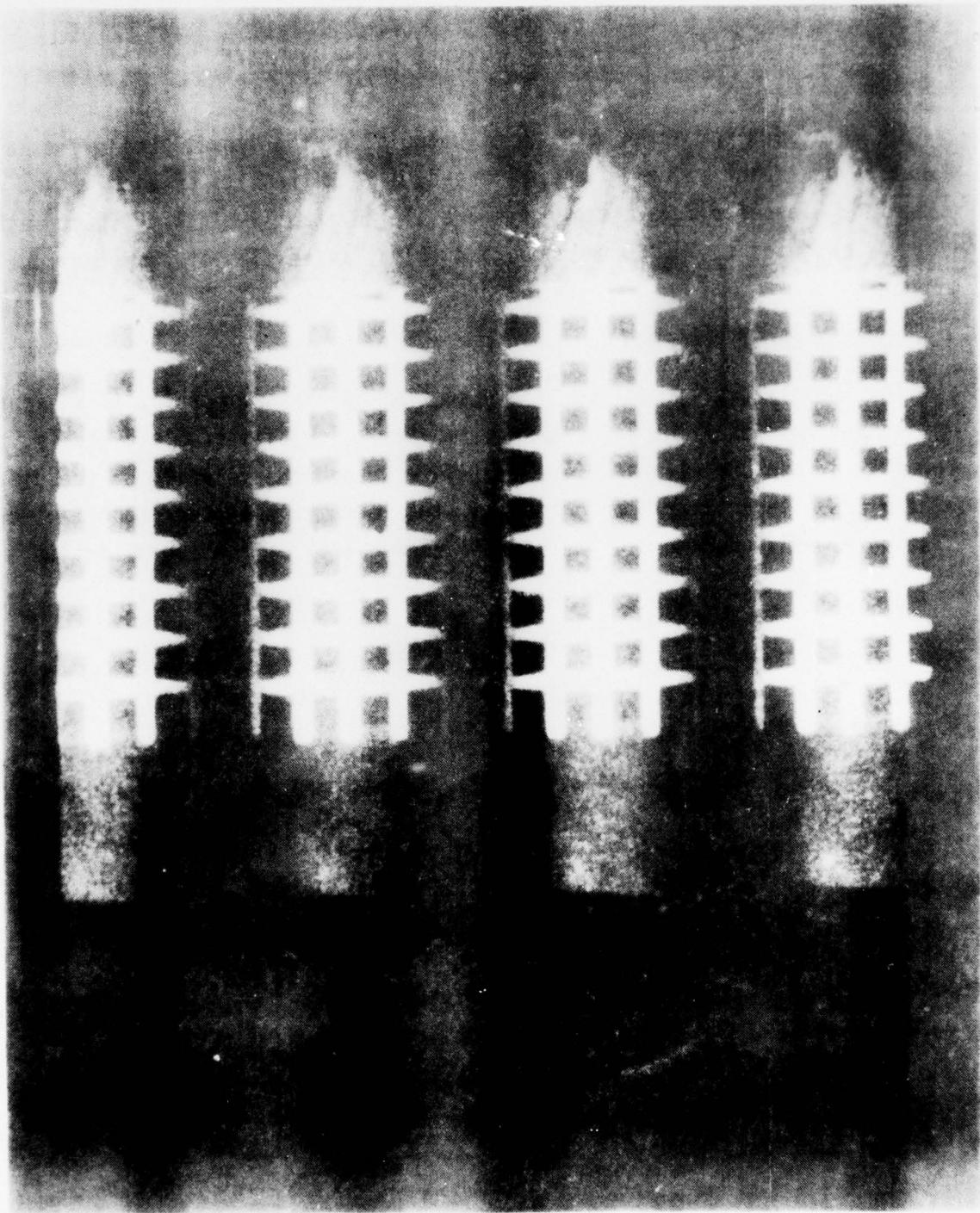


Figure 2. Fastax Film Strip for the 24.4 m/sec Impact Showing the Initiation of Impact Ignition

SECTION III

IMPACT PRESSURE CALCULATIONS

In this section, three methods of calculating the impact pressure as a function of impact velocity are presented, and the results of each method are compared. These calculation methods are (1) an ideally elastic impact method, (2) the Hugoniot reflection method, and (3) a finite element computer code method.

1. IDEALLY ELASTIC METHOD

The ideally elastic method, shown schematically in figure 3, is an approximation suitable only for low pressure impacts. For this simple analysis, the velocity of the propellant before impact is 0, and the velocity of the sled and of the propellant after impact is v_I . It is assumed that the propellant cross-section remains unchanged. The kinetic energy (KE) of the propellant is

$$KE = \frac{1}{2} \frac{W}{g} v_I^2 \quad (1)$$

where

$\frac{W}{g}$ = Propellant Mass



Figure 3. Schematic Diagram of the Ideally Elastic Impact

At the point of maximum deformation, the KE is assumed to be equal to the elastic energy of compression, and the potential energy (PE) is written as

$$PE = P_I \bar{\Delta V} \quad (2)$$

where

P_I = Impact Pressure

and

$\bar{\Delta V}$ = Change in Volume

For a constant bulk modulus, the impact pressure is also given by

$$P_I = K \frac{\bar{\Delta V}}{\bar{V}_0} \quad (3)$$

where

K = Bulk Modulus

and

\bar{V}_0 = Original Undeformed Propellant Volume

Setting $KE = PE$ and using equation (3) gives

$$P_I^2 = \frac{W V_I^2 K}{2 g \bar{V}_0} = \frac{\rho V_I^2 K}{2} \quad (4)$$

since

$$\rho = \text{Density} = \frac{W}{g \bar{V}_0}$$

The equation for the dilatational wave velocity in an extended medium is (ref. 4)

$$C_L = \left[\frac{\lambda + 2\mu}{\rho} \right]^{\frac{1}{2}} \quad (5)$$

where λ and μ are Lamé constants. The relation between Lamé constants

and the bulk modulus is (ref. 4)

$$K = \lambda + \frac{2}{3} \mu \quad (6)$$

Equations (5) and (6) can be combined to yield

$$K = C_L^2 \rho - \frac{4}{3} G \quad (7)$$

where

$G = \mu$ = Shear Modulus

Substituting equation (7) into equation (4) gives the impact pressure in terms of the velocity (V_I), assuming an ideally elastic impact,

$$P_I = V_I \left[\frac{\rho (C_L^2 \rho - \frac{4}{3} G)}{2} \right]^{\frac{1}{2}} \quad (8)$$

2. HUGONIOT REFLECTION METHOD

This method of calculating the impact pressure for a given impact velocity was taken from section 4.3 of reference 3. It is essentially a hydrodynamic approach (ref. 5) which utilizes a graphical technique and is based upon the shock Hugoniot of the UTP-3001 propellant and the steel plate of the impacting sled.

For the solid propellant, the shock Hugoniot given by Anderson (ref. 6) for any material having a density between 1 and 2 gm/cc was used:

4. Kolsky, H., Stress Waves in Solids, Dover Publications, Inc., New York, 1963.
5. Fowles, G. R., "Attenuation of the Shock Wave Produced in a Solid by a Flying Plate," Journal of Appl. Phys., Vol. 31, No. 4, pp. 655-661, April 1960.
6. Anderson, W. H., R. E. Brown, N. A. Louie and R. R. Randall, Vulnerability of Small Caliber Caseless Ammunition to Accidental Ignition, Report No. 3190-12, Shock Hydrodynamics, Sherman Oaks, CA, 1972.

$$P_I = \left[\frac{(10.6 + 43.8 \rho_0) 10^{-5} \rho_0 U_p^2}{(P_I - 10^{-5} \rho_0 U_p^2)} \right] + \left[\frac{(555 \rho_0 - 346) 10^{-10} \rho_0^2 U_p^4}{(P_I - 10^{-5} \rho_0 U_p^2)^2} \right] \quad (9)$$

where

P_I = Impact Pressure, kbars

U_p = Particle Velocity, m/sec

ρ_0 = Material Density, gm/cc

For steel, the Hugoniot equation relating shock velocity and particle velocity (in mm/ μ sec) is (ref. 7)

$$V = 5.38 + 0.251 U_p \quad (10)$$

By the conservation of momentum, the impact pressure in the steel as a function of particle velocity and shock velocity is (ref. 5)

$$P_I = \rho_0 U_p V \quad (11)$$

Combining equations (10) and (11) gives the impact pressure as a function of particle velocity

$$P_I = \rho_0 U_p (5.38 + 0.251 U_p) \quad (12)$$

The shock Hugoniots for UTP-3001 propellant and steel, equations (9) and (12), are shown graphically in figure 4. Also shown in the figure are the reflected steel Hugoniots about the three (24.1, 24.4, and 36.0 m/sec) impact velocity points. When the intersection coordinates of the reflected steel

7. Boyle, V. W., R. L. Jameson and M. Sultanoff, Determination of Shock Hugoniots for Several Condensed Phase Explosives, Fourth Symposium on Detonation, Naval Ordnance Laboratory, Silver Spring, MD, October 1965.

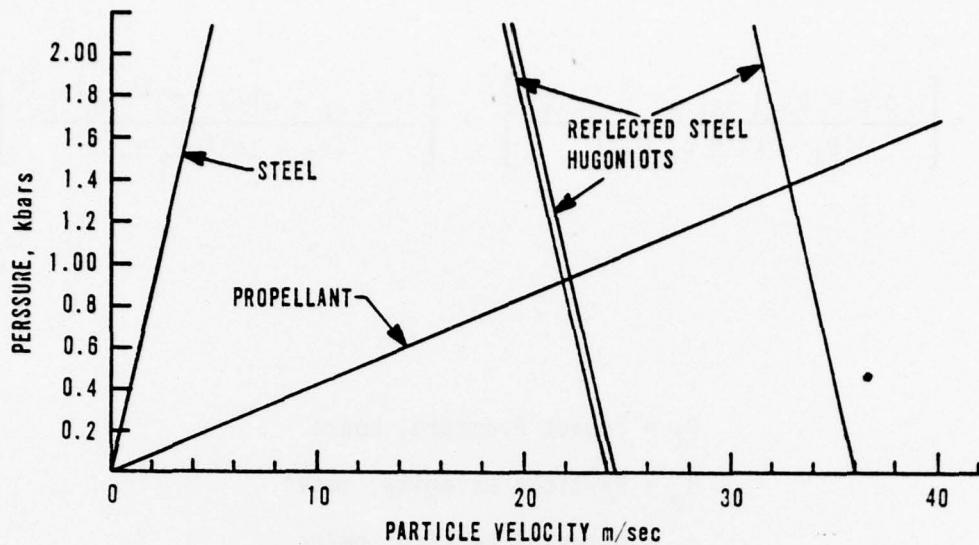


Figure 4. Shock Hugoniot Reflection Method for UTP-3001 Propellant and Steel Impacting Medium

Hugoniot with the propellant Hugoniot are plotted on log-log paper, an expression for impact pressure in terms of impact velocity is obtained. The log-log plot is shown in figure 5, and the resulting expression is

$$P_I = 0.0338 V_I^{1.06} \quad (13)$$

where

P_I = Impact Pressure, kbars

V_I = Impact Velocity, m/sec

3. FINITE ELEMENT COMPUTER CODE METHOD - HONDO

The axisymmetric finite element computer code HONDO was run for the three cases, using cylinders of height equal to the dimension of the respective cube and radius equal to the corresponding value for equal mass. The dimensions and masses for the three cases are shown in table 2, and the finite element mesh input to HONDO is shown in figure 6. The positioning of the mesh lines was chosen so that they were homologous with the edges of the painted grid lines on the UTP-3001 cubes.

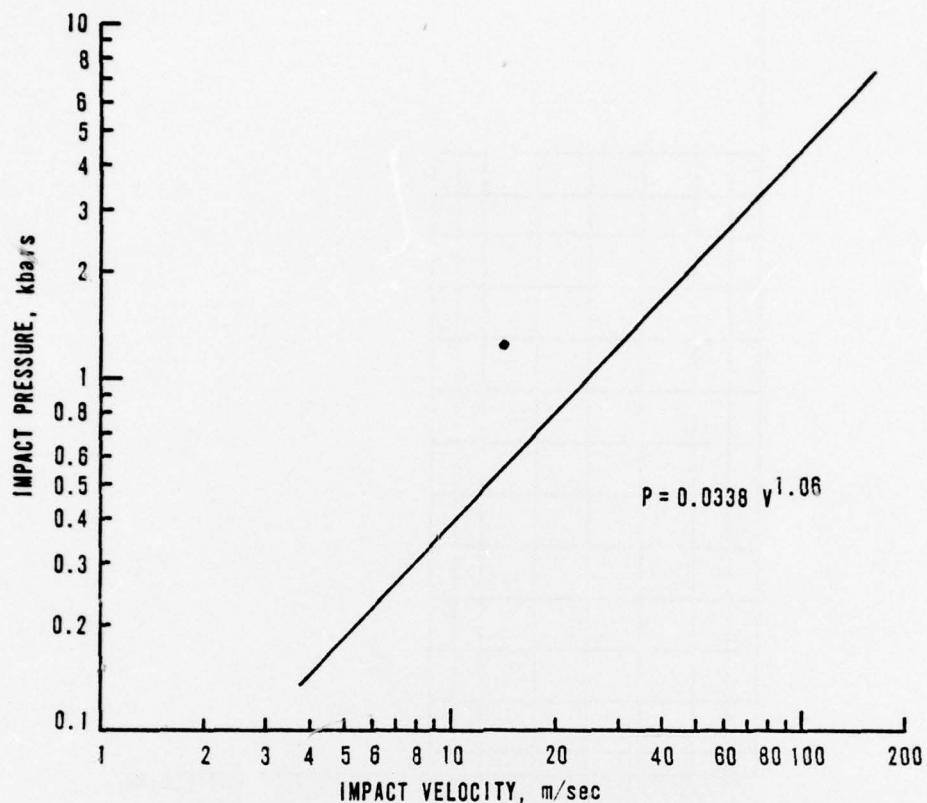


Figure 5. Shock Hydrodynamics Prediction of Impact Pressure versus Impact Velocity for UTP-3001 Propellant and Steel Impacting Medium

Table 2

DIMENSIONS AND MASSES OF THE IMPACT SPECIMENS AND THE HONDO CYLINDERS

<u>Impact Specimen Dimensions, cm</u>	<u>Mass, kg</u>	<u>HONDO Cylinder Dimensions, cm</u>
30.5 x 30.5 x 30.5	50.2	30.7 H x 34.3 D
30.5 x 30.5 x 40.6	66.8	40.9 H x 34.3 D
61.0 x 61.0 x 61.0	401.8	61.0 H x 68.8 D

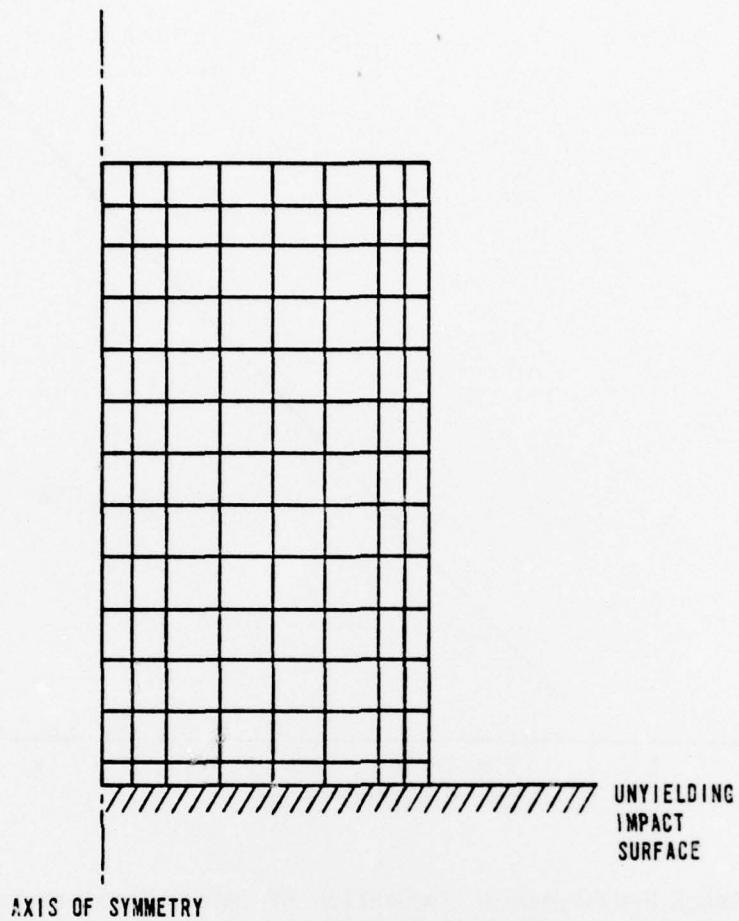


Figure 6. Finite Element Mesh Used by HONDO

The viscoelastic material model incorporated into HONDO was used for these impact simulations. This material model uses a shear relaxation modulus which has the form (ref. 8)

$$G(t) = G_{\infty} + (G_0 - G_{\infty})e^{-\beta t} \quad (14)$$

8. Key, S. W., HONDO - A Finite Element Computer Program for the Large Deformation Dynamic Response of Axisymmetric Solids, SLA-74-0039, Sandia Laboratories, Albuquerque, NM, April 1974.

The short-term modulus (G_0) and the long-term modulus (G_∞) were obtained from the general expression for the UTP-3001 shear relaxation modulus (ref. 9)

$$G(t) = 76.6 + 51.6 e^{-0.0005t} + 11.7 e^{-0.005t} + 58.6 e^{-0.05t} + 103 e^{-0.5t} + 186 e^{-5t} + 424 e^{-50t} \quad (15)$$

where $G(t)$ is in psi, t is in minutes. For times less than 10 msec, very small error is introduced by reducing the equation to

$$G(t) = 487.5 + 424.0 e^{-0.833t} \quad (16)$$

The pressure histories obtained by the HONDO calculations at a point 0.635 cm from the impact plane are shown in figures 7 to 9.

The calculated and observed deformations of the grid lines are shown in figures 10 to 15 at 3.81 cm and 8.89 cm from the impact plane. The deformations are plotted as $(-\Delta U/U)$, where ΔU is the change in length and U is the original length of the grid line.

4. COMPARISON OF THE THREE IMPACT PRESSURE CALCULATION METHODS

The impact pressures calculated by the ideally elastic (eq. 8), the Hugoniot reflection (eq. 13), and the HONDO methods are shown in figure 16. The pressures obtained for the three impact velocities tested, as well as for two additional (60 m/sec, 90 m/sec) velocities, are shown for comparison in the figure. The numerical values for the test velocities are shown in table 3.

Since the ideally elastic impact assumption is valid only for low velocity and pressure impacts, and the Hugoniot reflection method was developed for small projectiles and high velocities and pressures, the actual impact pressures for the sled velocities used for these UTP-3001 impacts are expected to be somewhere between the two. Table 3 and figure 16 show that the HONDO calculations predict the pressures to be between these two limits.

9. Private Communication between Charles M. Craft and Eugene Francis, United Technology Center, Sunnyvale, CA, 15 August 1974.

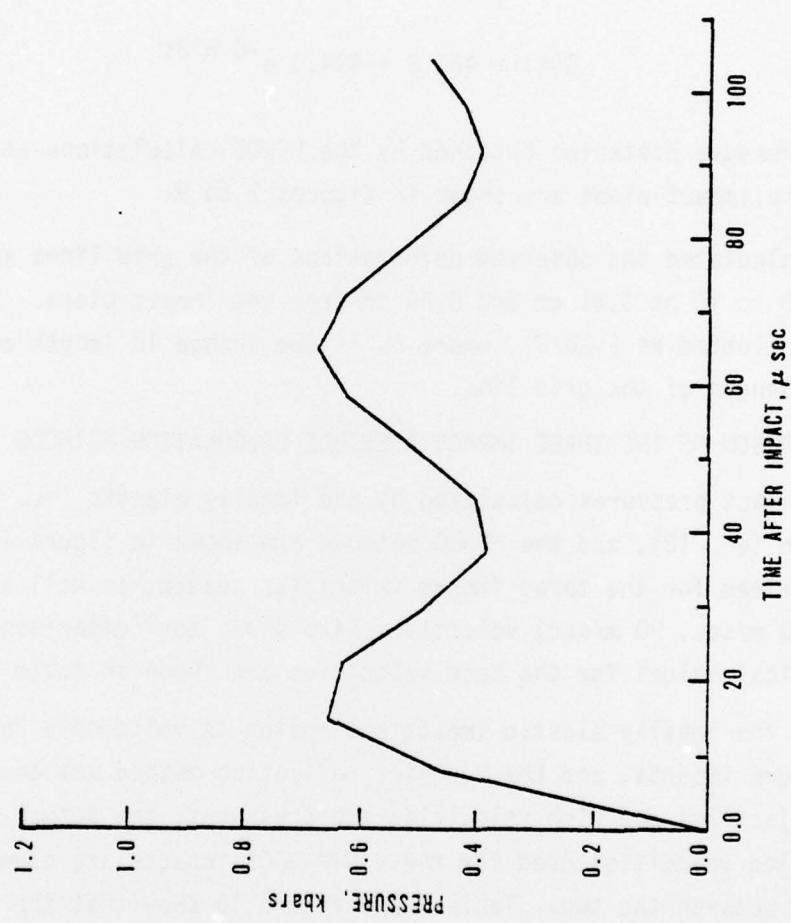


Figure 7. Pressure versus Time After Impact for 24.1 m/sec Impact at 0.635 cm from the Impact Plane and 0.794 cm from the Cylinder Axis

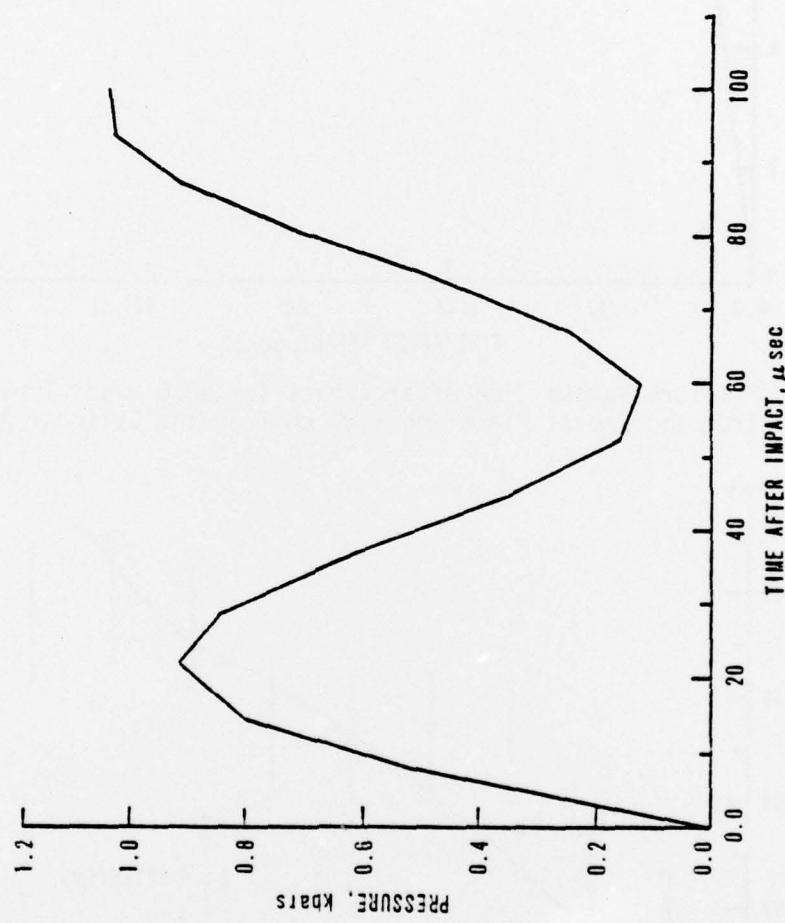


Figure 8. Pressure versus Time After Impact for 24.4 m/sec Impact at 0.635 cm from the Impact Plane and 0.794 cm from the Cylinder Axis

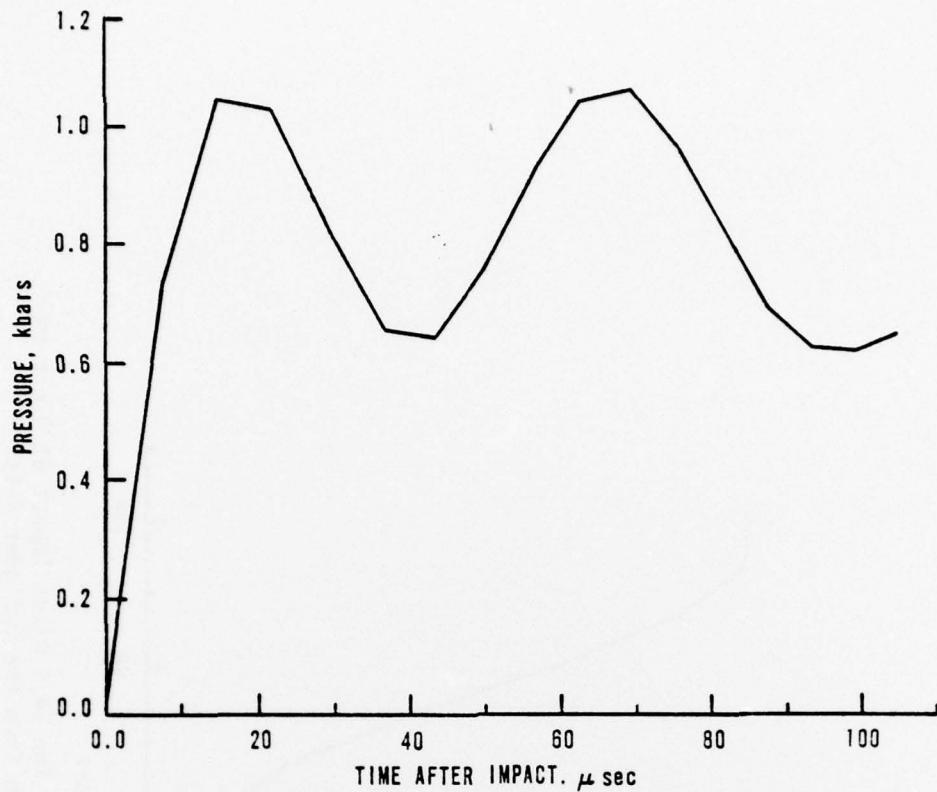


Figure 9. Pressure versus Time After Impact for 30.6 m/sec Impact at 0.635 cm from the Impact Plane and 1.32 cm from the Cylinder Axis

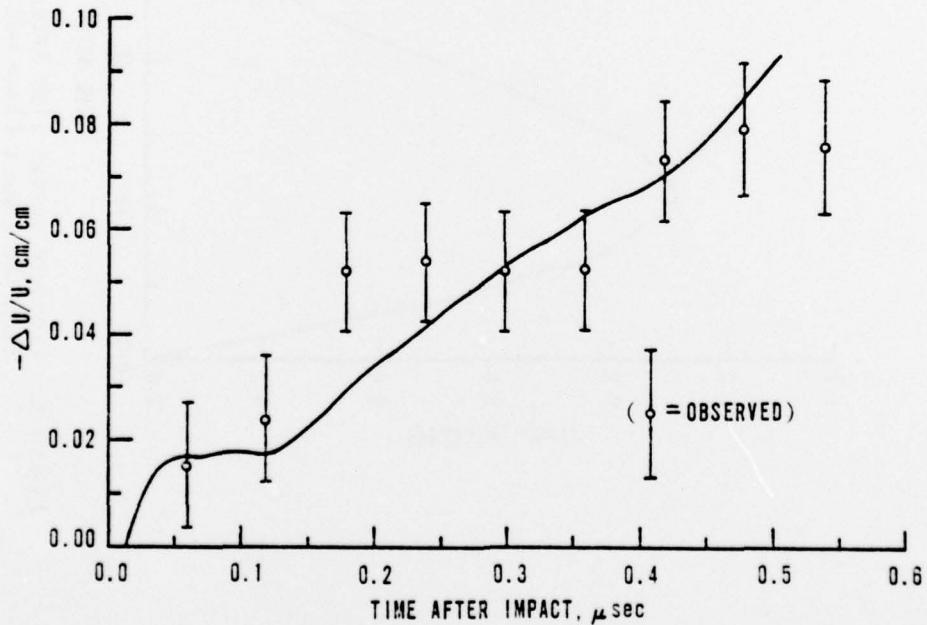


Figure 10. Observed Deformations and Those Predicted by HONDO for the 24.1 m/sec Impact at 3.81 cm from the Impact Plane

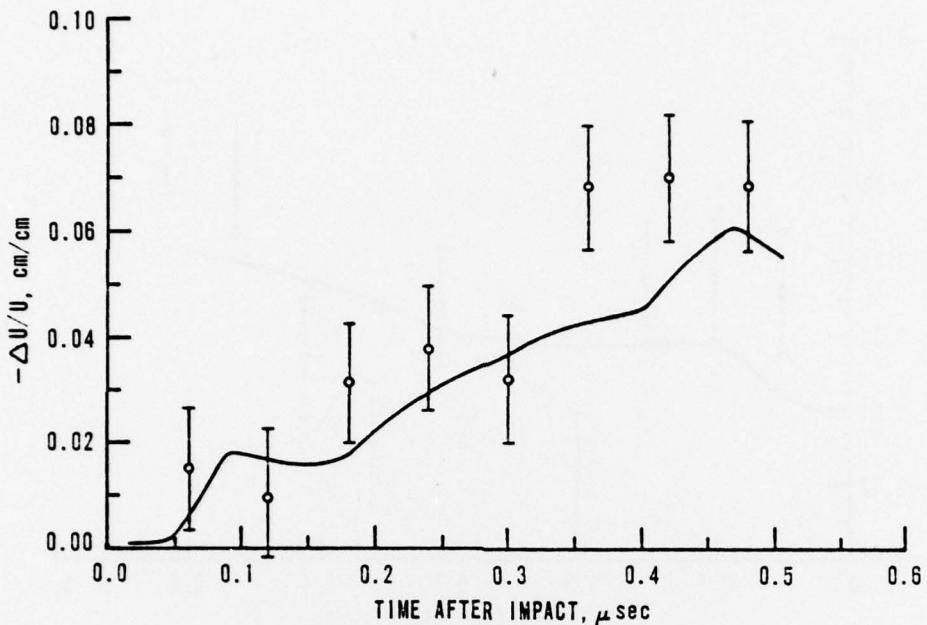


Figure 11. Observed Deformations and Those Predicted by HONDO for the 24.1 m/sec Impact at 8.89 cm from the Impact Plane

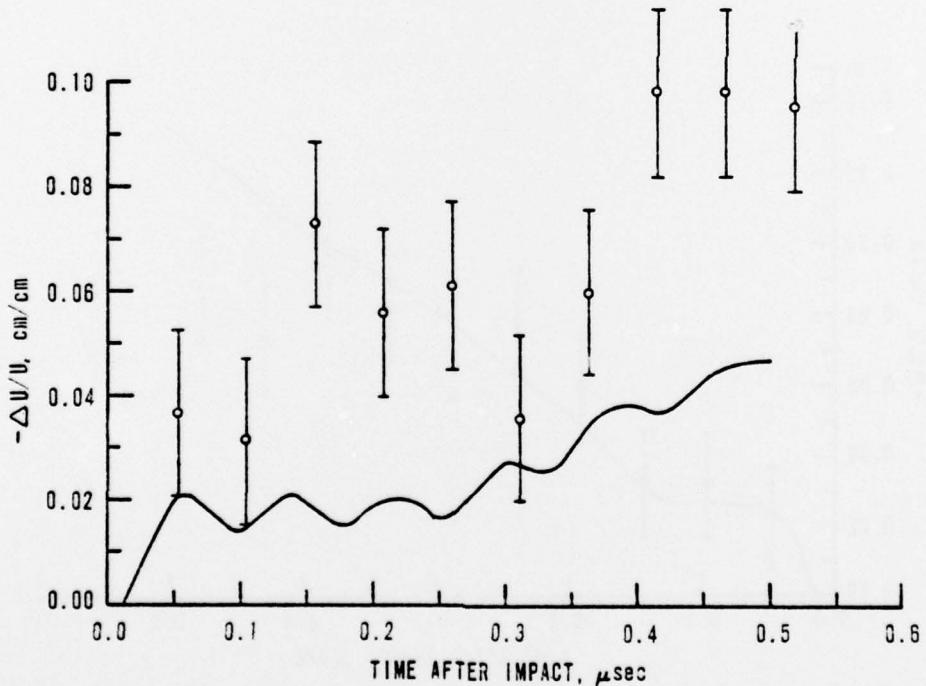


Figure 12. Observed Deformations and Those Predicted by HONDO for the 24.4 m/sec Impact at 3.81 cm from the Impact Plane

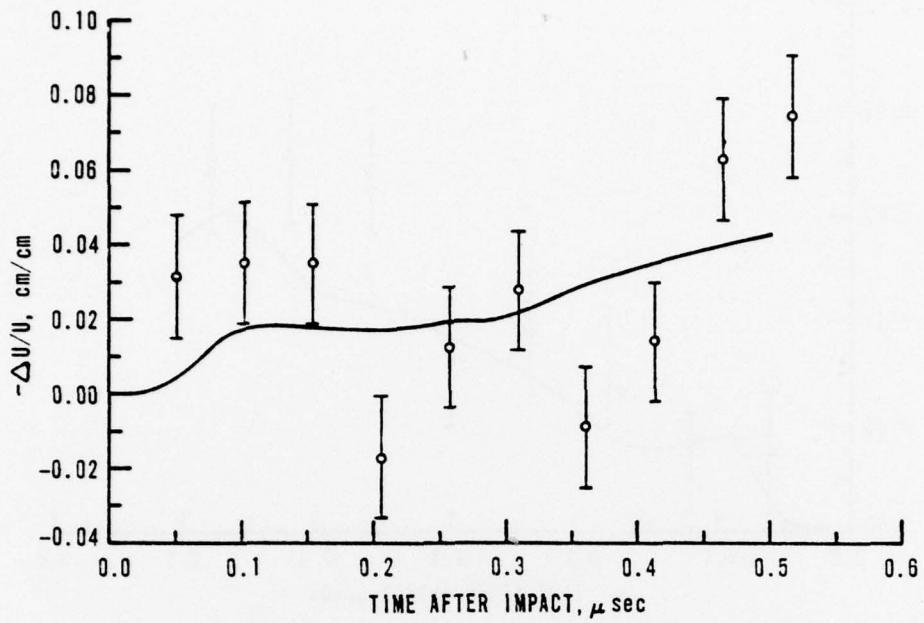


Figure 13. Observed Deformations and Those Predicted by HONDO for the 24.4 m/sec Impact at 8.89 cm from the Impact Plane

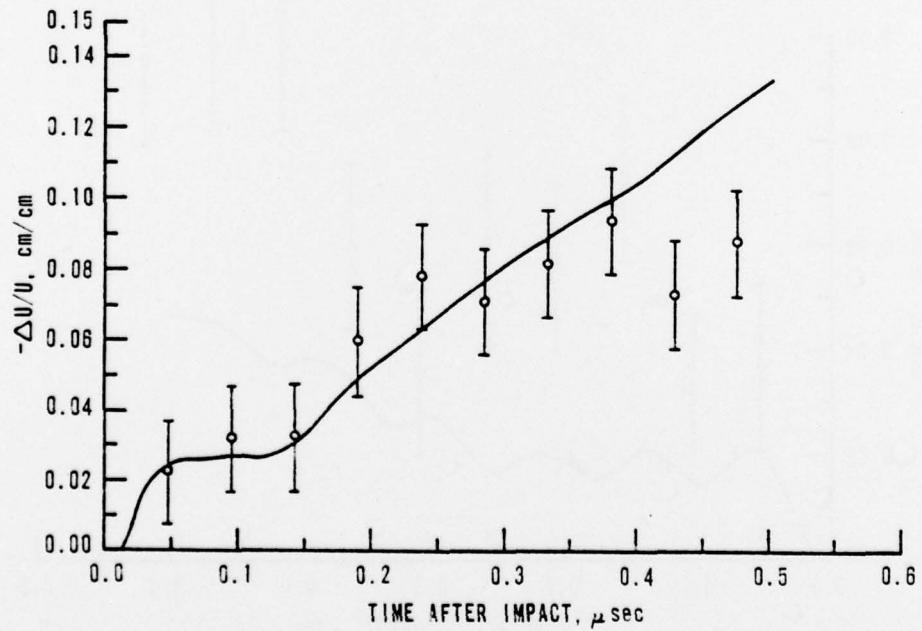


Figure 14. Observed Deformations and Those Predicted by HONDO for the 36.0 m/sec Impact at 3.81 cm from the Impact Plane

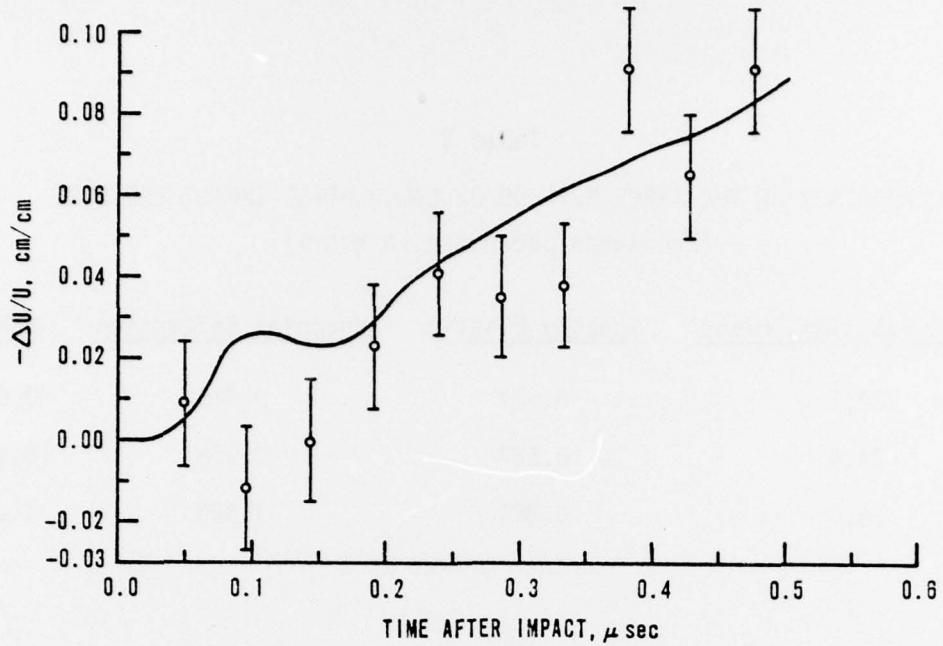


Figure 15. Observed Deformations and Those Predicted by HONDO for the 36.0 m/sec Impact at 8.89 cm from the Impact Plane

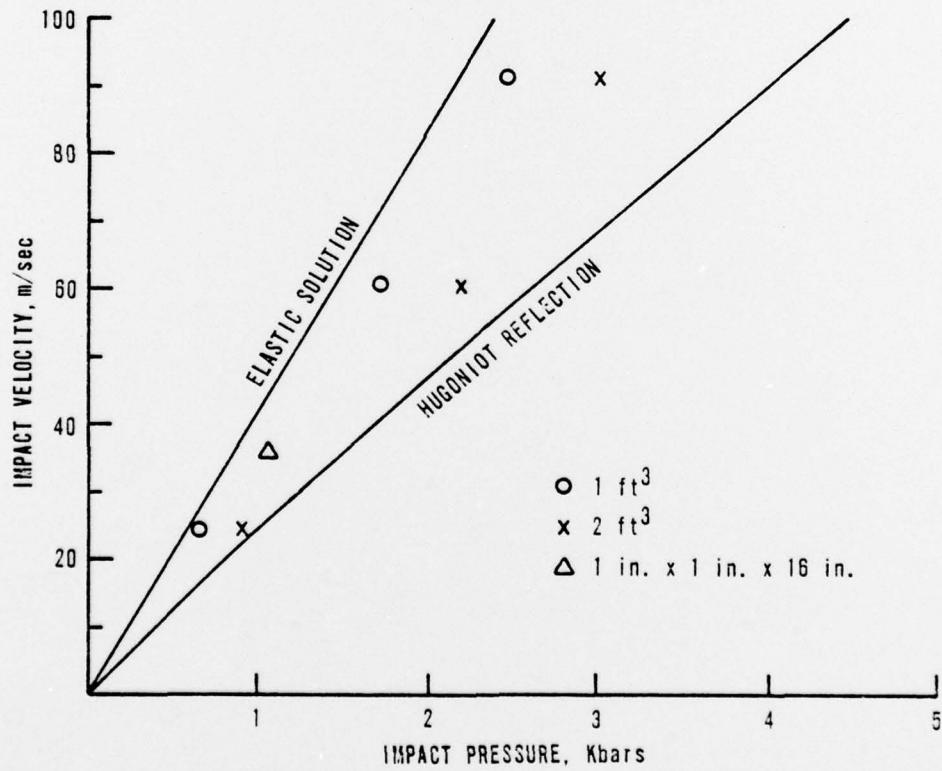


Figure 16. Comparison of the Three Impact Pressure Calculation Methods

Table 3

COMPARISON OF THE THREE METHODS OF CALCULATING IMPACT PRESSURE
(Pressures Shown Are in kbars)

<u>Impact Velocity, m/sec</u>	<u>Ideally Elastic</u>	<u>Hugoniot Reflection</u>	<u>HONDO</u>
24.1	0.577	0.985	0.672
24.4	0.584	0.998	0.914
36.0	0.861	1.509	1.063

SECTION IV

CONCLUSIONS

The UTP-3001 ignition sensitivity to impact results is given for reference purposes for any future ignition model development or correlation.

The applicability of the axisymmetric finite element computer code HONDO for calculating stresses and deformations in UTP-3001 solid propellant is shown for impacts of 79 to 118 fps (24.1 to 36.0 m/sec). The HONDO code, or another code which utilizes similar viscoelastic material subroutines, will be the primary analytical tool used for guidance and a better understanding of the sub-scaled and full-scale solid rocket motor impact tests. The HONDO code (or other finite element code) becomes an invaluable tool when two materials must be modeled (e.g., viscoelastic solid propellant and elastic-plastic steel casing).

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5. Fowles, G. R., "Attenuation of the Shock Wave Produced in a Solid by a Flying Plate," Journal of Appl. Phys., Vol. 31, No. 4, pp. 655-661, April 1960.
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